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Title: Fukushima-Daiichi Muon Tomography

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Fukushima-Daiichi Muon Tomography

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on behalf of

LANL-KEK collaboration

Purpose of the Project

The 9.0-magnitude earthquake followed by the vast tsunami on March 11th caused ongoing nuclear crisis at Fukushima Daiichi [1]. Failure of the Fukushima Daiichi reactors is attracting the world-wide attention to the issue of fundamental safety of atomic energy. In spite of the intense effort by Tokyo Electric Power Company (TEPCO) and the Japanese government, reactor #1-3 are likely to be in the meltdown states. Though the reactors are gradually stabilizing, there is small but undeniable possibility of recriticality due to the recent detection of ^{135}Xe from Reactor #2. The recovery and decommission process are unpredictable without any realistic estimation of the amount and location of the melted fuel as well as extent of the damages to the reactors. In the case of Three Miles Island, it took more than 3 years before a "quick look" camera could be put into the reactor, and about 10 years before the total damage to the reactor could be assessed.

One possible technique to investigate the reactors without accessing to the cores is "muon imaging" that utilizes naturally occurring cosmic-ray muons to image large scale objects. Cosmic-ray muons are the shower of muons which have a flux of 10^4 muon/min·m^2 [2] with mean energy of 3~4 GeV and are highly penetrative. Because muons are not attenuated by nuclear interactions, their range in material is only limited by the energy-loss process. This makes muon radiography (MR) an excellent tool for studying the inner structure of thick and/or dense substances. Since the 1950s, MR technique has been applied to study large-scale objects such as mine overburden [3], Egyptian pyramids [4], volcanoes [5] and a blast furnace [6]. The MR technique is similar to roentgenograph in that the attenuation of particles in materials is used to shadow an object.

On the other hand, muon tomography (MT) technique was developed in the last 10 years. It started at Los Alamos National Laboratory (LANL) as a special project in response to the 9/11 terrorist attack. MT measures multiple Coulomb scatterings of cosmic-ray muons in an object [7] instead of attenuation. The technique has been applied to practical uses such as scanning trailer or shipping containers for nuclear materials [8], and we note that the LANL development of MT was identified as one of the "top 100 inventions of 2010" by Popular Science Magazine. The MT technique is similar to MRI in that the locations of specific atoms in an object are detected to reconstruct a 3-dimensional image.

The purpose of this project is to reveal the conditions of the reactor cores of Fukushima Daiichi by using the MT technique. Muons are deflected more strongly by heavy nuclei like uranium than by relatively lighter nuclei like the iron in steel or the elements in concrete, since multiple Coulomb scattering is approximately proportional to the nuclear charge. This is a big advantage of the MT technique to investigate the damaged reactors because a map showing regions of large muon deflection will identify the location of uranium, in contrast to lighter nuclei.

This project will provide images that show the location of fuel – showing if it is undamaged, or that fuel rods have been damaged and fuel has collected in lower regions of the pressure vessel, or the fuel has collected in the dry well. Measuring and establishing any of these conditions in a short time will provide valuable input for decisions about how to proceed with recovery and decommission of Fukushima Daiichi. If it is determined all of the fuel has been contained in the RPV, the cleanup and remediation of the site might be much less complex than if substantial fuel has leaked from the RPV and migrated to lower levels of the building. If there is extensive damage to the fuel of a nuclear reactor, the MT technique could be used to identify voids in the fuel structure, or abnormal presence of fuel in lower regions of the reactor pressure vessel (RPV). Also, the technique would yield a reliable measurement of the mass of uranium present in a given volume. Since the initial fuel load is known, measuring a deficit would indicate the amount of fuel which has escaped the reactor vessel – a so-called "melt down" condition. The MT techniques would be the best and the only way to provide this information within the next couple of years for Japanese decision makers.

We formed a LANL-KEK collaboration to apply our MT technique to Fukushima Daiichi to investigate the nature of the damage so that appropriate strategies for recovery and decommission can be developed. Our goal is to assess extent of damages of reactor cores and provide precise information to Japanese decision makers in a short period of time. To accomplish our goal, muon detectors of a large area are inevitable because a measurement time to reconstruct an image is inversely proportional to S^2 for MT, and to S for MR, where S is the area of a muon detector.

Our current scenario at Fukushima Daiichi is to set up a pair of Giant Muon Trackers (GMT) outside the reactor building (*fig.1*) to measure incoming and outgoing tracks of cosmic-ray muons, since the building access is not easy at the current stage. GMT has a large detection area of 11×5 m^2, which allows reconstruction of a reactor-core image in 2 weeks. GMT can be operated in MT and MR mode simultaneously. We will also install a KEK detector which is operated in MR mode. MR technique developed at KEK uses smaller detectors and may produce useful results especially if we could install the detector near the reactor core *e.g.* basement of the reactor building.

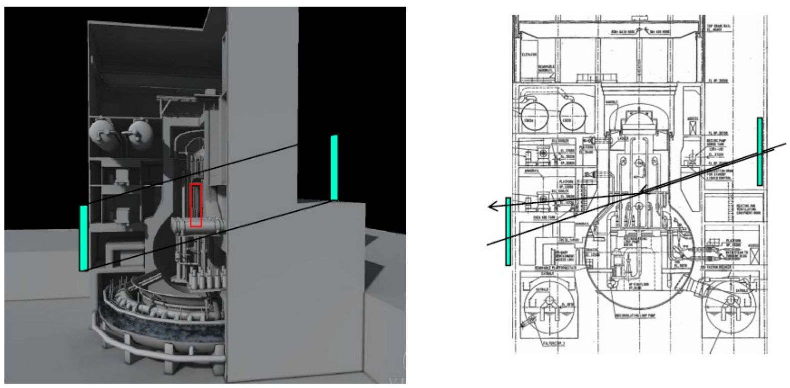

Figure 1: Proposed detector setup for Fukushima Daiichi. Two muon trackers will be installed near the wall of the reactor building. The two muon trackers would be ~50-m apart.

In the meantime, the US Nuclear Regulatory Commission (NRC) has warned that the similar disaster could take place at the US reactors. In the emergency situation like Fukushima Daiichi, MT would provide significant information to work on countermeasures and allow assessing damage. This project would not only benefit Japan but also American tax payers by implementing additional security to the nuclear reactors in the US as well as advancing a bilateral comity between the two nations.

We request the Fukushima-Daiichi Muon Tomography project to be supported by the Japanese and the US government at the equal level of 4-million dollars (= 3.2-oku Yen). We would like funding from the Japan to cover equipments such as muon trackers, radiation shields and their mechanical supports. Because they are likely to get contaminated at Fukushima Daiichi, we consider it is appropriate for Japan to own these equipments. The Japanese share also includes costs to install muon trackers to Fukushima Daiichi, and continue the measurements for 12 months. LANL will transfer the MT technology to KEK so that TEPCO can keep monitoring the reactors even after the current project is over.

We request US Department of Energy (DoE) to fund our simulation work, data-acquisition system (DAQ) and software improvements, data analysis, and support for LANL personnel. Under the US funding, simulation for case study, system optimization to cope with the high-radiation environment, and data analysis on Fukushima Daiichi measurements will be performed. The US funding also covers a possible technical demonstration at a US reactor site, which KEK team will also join. The demonstration was requested by the Japanese government recently, and LANL management has been negotiating with DoE and a US power company in the east coast that owns Boiling Water Reactors (BWR).

We note that the MT technique has a potential to be installed to every nuclear reactor in the world, and could be the basis for a world-wide large-scale application to help address nuclear-safety issues. The lack of effective monitoring system caused chaotic situation at Fukushima Daiichi and at Three Mile Island, which MT could have definitely helped. We hope Japan and the US consider the impact of the current project to the extent of the worldwide atomic-energy safety that has been questioned since March 11th.

[1] G. Brumfiel and D. Cyranoski, *Nature* 471, 273 (2011).
[2] K. Hagiwara, *et al.*, *Phys. Rev. D* 66, 1 (2002).
[3] E.P. George, *Commonwealth Engineer* (July 1, 1955) 455.
[4] L.W. Alvarez, *et al.*, *Science* 167, 832 (1970).
[5] K. Nagamine, *et al.*, *Nucl. Instr. and Meth. A* 356, 585 (1995).
[6] K. Nagamine, *et al.*, *Proc. Jpn. Acad. B* 81, 257 (2005).
[7] K.N. Borozdin, *et al.*, *Nature* 422, 277 (2003).
[8] C. Morris, *et al.*, *Science & Glorbal Security* 16, 37 (2008).

State of Preparations for the Project

After the vast disasters caused by the great earthquake and tsunami in eastern Japan, we proposed applying our MT technique to help and improve the emergency situation at Fukushima Daiichi. A reactor-tomography team was formed at LANL which was supported by the laboratory as a response to a request by the former Japanese Prime Minister, Naoto Kan.

We carried out a technical demonstration using a reactor mockup, Monte Carlo simulations and a detector test under high-radiation backgrounds. So far, we have established the feasibility of applying the MT technique to tomograph Fukushima Daiichi reactors. Additional demonstration in the US with a working reactor would reduce the potential risk of Fukushima Daiichi measurements to zero.

We note that most of the works in this section were carried out by spontaneous efforts of LANL scientists who felt sympathy to the victims of the disaster on March 11th.

<u>Mockup demonstration</u>

The reactor mockup tests were performed at LANL to prove the principle of "reactor tomography" and to optimize our MT algorithm to image a reactor core through thick concrete walls. It was a new challenge in the sense that the existing MT technique uses downward-going (vertical) muons. The incident flux of cosmic ray muons is greatest in the vertical orientation, but the flux of horizontal-going muons is also significant above 1-GeV energy. It is these horizontal-going muons that are well suited to the geometry required for making an image of the uranium inside the pressure vessel of the reactors.

In our demonstration, we measured cosmic-ray muons passing through a physical arrangement of material similar to a nuclear reactor, with thick concrete shielding and a heavy metal core. About 5 tons of lead were used to construct a mockup core. At BWR of the type installed at the Fukushima Daiichi plant, concrete shielding is about 3-m thick. In terms of scattering length, 0.7-m of lead is equivalent to the uranium in a reactor core, however, the uranium core should be easier to see than the lead target with the MT technique because of larger atomic number. The trajectories of cosmic ray muons were measured with two tracking detectors composed of gas-filled ionization drift tubes. We used Mini Muon Tracker (MMT) of 1.2×1.2-m^2 area (and 0.5-m thick), and had three pairs of x-y planes: MMT is significantly smaller than GMT (11×5.5-m^2), however, the acceptance of cosmic-ray muon is approximately the same with the geometry we plan at Fukushima Daiichi.

Several target arrangements were studied for specific features of the technique. They were: (a) no target, (b) lead with conical void, (c) lead quadrants, (d) lead resolution column, and (d) lead and iron contrast column. A rate of good events that made through two detectors was 1~2 event/min. It took about a week to take one image. The conical void target was similar in shape to the melted core of the Three Mile Island reactor; lead quadrants were studied to demonstrate differentiation between varying thicknesses; lead resolution column was optimal for determining spatial resolution; and contrast column was used to measure capability of differentiating between fuel and the reactor pressure vessel (RPV).

Data were analyzed in two steps. First, ingoing and outgoing tracks were reconstructed in the data acquisition computer and stored for later analysis. Second, track pairs were projected to the mid-plane of the target. Some of the results are shown in *fig.2* and *3*.

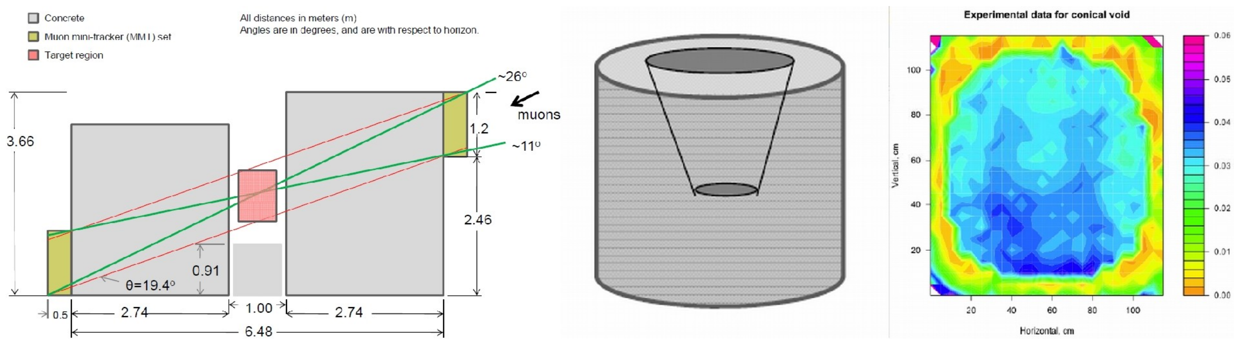

Figure 2: Schematic view of demonstration experiment using reactor mock up (left). Reactor core mockup was rephotographed through concrete shields of 6-m thickness. Several configurations of interior material were studied, such as large masses of Pb bricks with conic void (center) which was successfully observed (right).

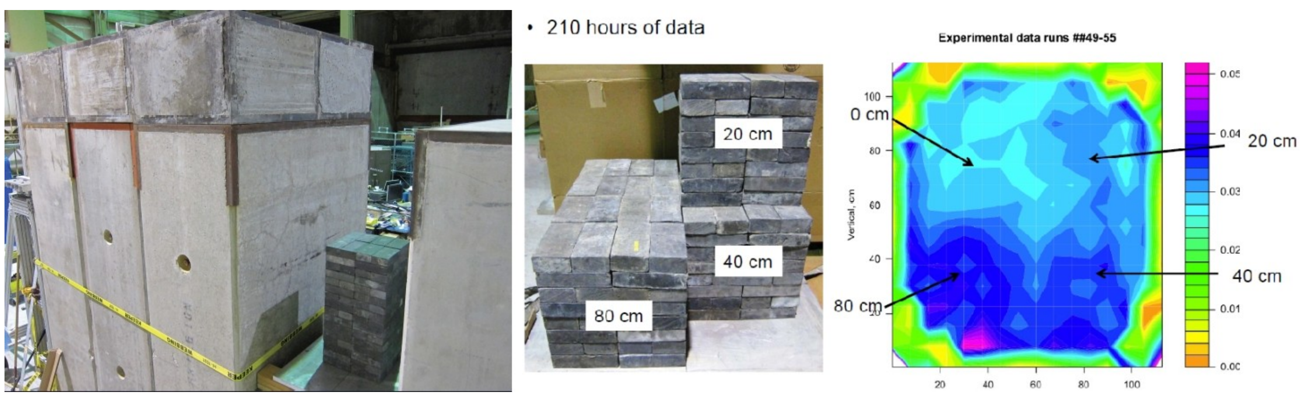

Figure 3: Photo of the demonstration (left). Lead targets of 20-, 40- and 80-cm thickness were tomographed through concreat wall of 6-m thickness (center, right).

The analysis clearly shows the outline and structure of the targets, identifying the location of lead inside the concrete walls. Newly developed algorithms were used to reconstruct an image of the “mock reactor core”, demonstrating a resolution of approximately 0.2 m.

Thanks to the larger detector area of GMT, the expected rate of “good event” at Fukushima Daiichi is 40 times higher than the demonstration. The rate would be as high as 100 event/min and it requires about 10^6 events to reconstruct an image. It is expected that we could take an image of a reactor core in 2 weeks. Further data-accumulation of 2~6 months would assess detail of the damage.

<u>Simulation study</u>

We performed GEANT4 Monte Carlo simulations [9] of our mockup demonstrations. The standard cosmic ray muon spectrum in GEANT4 is for downward-going (with zenith angle zero) muons. The near-horizontal-going muons accepted by our apparatus, spanning angles approximately 11~26 degrees above the horizon have a different spectrum, which we have substituted for the standard spectrum. The results of the simulations show good agreement with the reconstructed image data of our mockup demonstration. This proved the correctness of the GEANT 4 code to predict Fukushima Daiichi measurements.

Using drawings obtained from TEPCO, we specified a GEANT4 geometry approximating the Fukushima Daiichi Unit Number 1 (*fig.4*), which is a General Electric BWR Mark-1 reactor. According to the simulation, our MT can image the reactor-core approximately in two weeks measurement. The MT technique could provide crucial data to decision-makers, to help guide remediation plans.

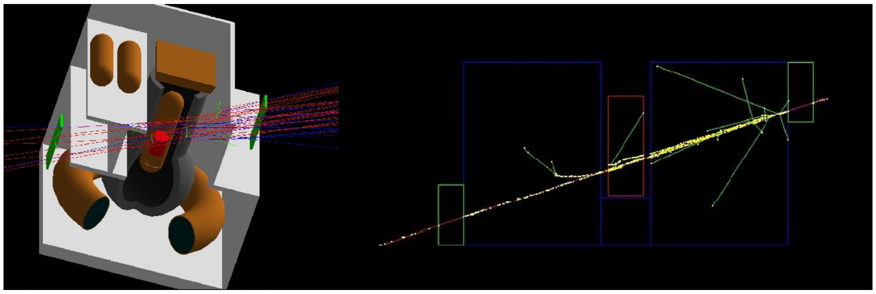

Figure 4: Geant-4 simulation of Fukushima-Daiichi Reactor #1.

A comparison of MT and MR technique was performed with the GEANT 4 simulation (*fig.5*). The simulations was performed for the same detector size (1.2×1.2-m^2) and measurement time (10^6 muons).

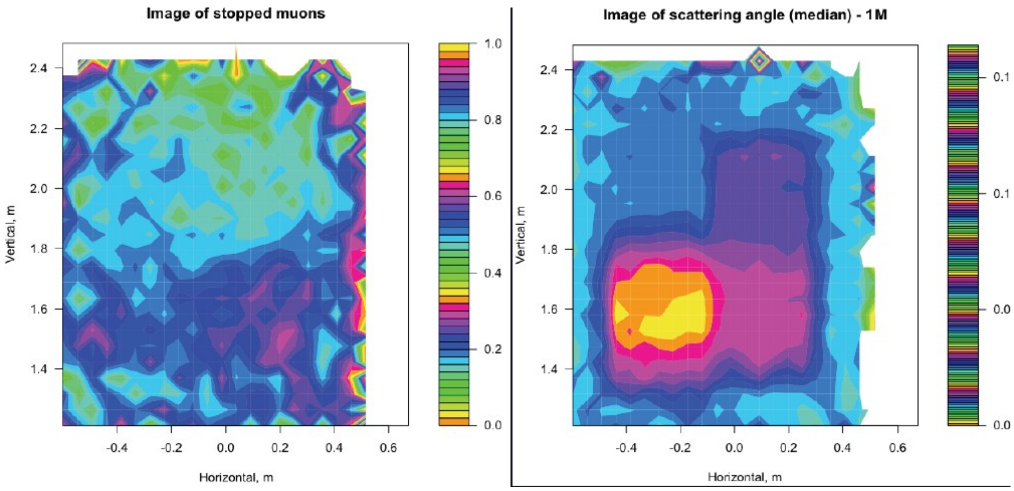

Figure 5: Geant-4 simulation of lead quadrants demonstration for MR (left) and MT (right).The lead quadrants were sandwiched by two concrete walls of 3-m thickness (6 m in total).

We note that, both MT and MR have advantages and disadvantages for reactor imaging. GMT can accumulate data quickly because of the large detector area, and MT technique has an advantage in tomographing uranium through thick concrete shields. On the other hand, KEK detector has a moderate size and solid-angle acceptance, and it is made of robust fast-rising-time photomultipliers. KEK detector could be installed near a reactor core when the radiations inside the reactor building decreased to a reasonable level. In that situation, data from the both teams would complement each other and should be combined to assess the damages of the reactors as precise as possible.

Drift-tube test under high radiation

One engineering challenge at Fukushima Daiichi is a radiation shield of GMT. Under a high radiation background, it is known that random coincidences blind ionization drift-tube detectors. Drift tubes are less sensitive to gamma rays (1-% efficiency at 1 MeV) compared to PMTs with plastic scintillators but have longer dead time (~5 μs). For a radiation damage, drift-tubes with Ar–CO_2 (93–7%) gas are known to be less affected by the radiation damage or aging caused by intense γ-rays [10] but their electronics may need to have some protection [11]. In our case, both the drift tubes and the electronics will be heavily shielded. Conditions of the drift tubes will be monitored by the DAQ.

We tested a drift-tube detector in contaminated sections of Proton Storage Ring (PSR) at Los Alamos Neutron Science Center (LANSCE). We also performed some tests with concrete shields to demonstrate γ-ray attenuation (*fig.6*). The major source of the background at LANSCE-PSR was 834-keV γ ray from ^{54}Mn electron-conversion decay which is a good simulation of γ rays at Fukushima Daiichi. It was reported that the main sources of γ-ray background at Fukushima Daiichi were ^{134}Cs and ^{137}Cs.

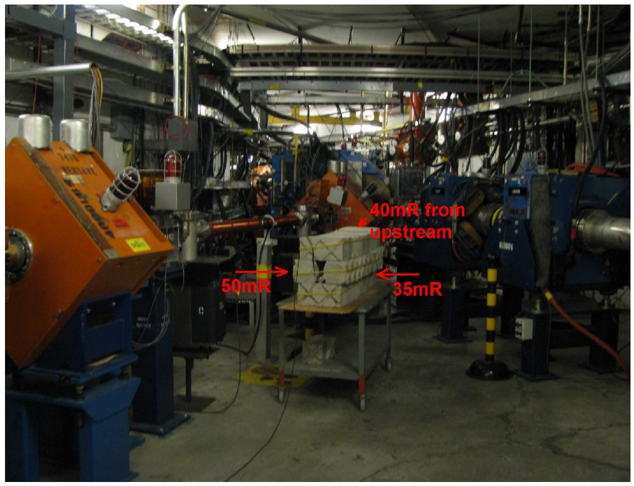

Figure 6: Drift-tube test in one of a hot area of LANSCE PSR (Zone 1, Section 2).

The resolving time of our drift tubes is 1 μs and single rates in tubes higher than 20 kHz will begin to cause a problem. For a practical use of GMT, the background should be less than 1 kHz. The muon-event rate at Fukushima Daiichi is expected to be ~40/s for a single drift tube (for 2π acceptance).

The counting rate caused by the γ-ray was 690~780 kHz/mSv for the GMT drift-tube. In our current scenario, a plastic cases that hold water of 1-m thickness will be used to protect our GMT from γ-ray backgrounds at Fukushima Daiichi. Low-Z materials are suitable for the shield because it induces less muon scattering. As shown in *table 1*, water of 1-m thickness reduces γ-ray intensity by 3~4 orders of magnitude for the major lines [12]. Water of 1-m thickness has γ-ray buildup factor of 1.2 and 1.4 for 500-keV and 1-MeV energy [13] which account for contributions from Compton scattered photons. The actual attenuation of γ-ray intensity can be described as follows: $I = B{\cdot}I_0 \exp(-\mu x)$. With the water shielding of 1-m thickness, it is safe to assume that the current GMT detector can operate stably in a Fukushima Daiichi's radiation environment of 1 mSv/h. We will upgrade our electronics so that GMT could be operated even under 4-mSv/h environment.

Table 1: Attenuation of γ-rays from ^{134}Cs and ^{137}Cs by 1-m water. ^{134}Cs emits more than one γ rays so the total of branching ratio is larger than 100%.

E [keV]	B.R. [%]	λ [cm]	Attenuation
Cs134			
563	8.4	10.8	9.8E-05
569	15.4	10.9	1.0E-04
605	97.6	11.2	1.3E-04
796	85.5	12.7	3.8E-04
802	8.7	12.7	3.9E-04
1,365	3.0	16.4	2.2E-03
Cs137			
662	85.1	12.2	2.7E-04

Though the LANSCE-PSR test provided a good estimation for the radiation-shield thickness of GMT, a drift-tube test at Fukushima Daiichi must be made to confirm it. Background rates could differ by an order of magnitude depending on the types and locations of the sources around the reactor buildings. However, our estimation here is close to the worst-case scenario and we do not expect any show stoppers.

[9] J. Allison *et al.*, *IEEE Trans. on Nucl. Sci.* 53 (2006) 270.
[10] C. Adorisio *et al.*, *Nucl. Instr. and Meth. A* 535 (2004) 186.
[11] G. Avolio *et al.*, *Nucl. Instr. and Meth. A* 568 (2006) 624.
[12] J.H. Hubbell, *Int. J. Radiat. Isot.* 33 (1982) 1269.
[13] ANS Standard, *ANSI/ANS-6.4.3-1991*.

Project Plan and Schedule

This section describes tasks and schedule of the project. These are preliminary estimates of schedule and will be revised based on continued discussions between LANL, KEK and TEPCO, and updates regarding Fukushima-Daiichi site (radiation levels, clean-up activities, etc.). The following table shows the three stages of the project.

<u>Stage 1</u> (3 months)

Planing (1 month)

- Planning for Fukushima Daiichi measurement.
- Design radiation shields.
- Simulation studies.

Acquire equipments (3 month)

- Manufacture GMT/radiation shields.
- DAQ and software improvements.

<u>Stage 2</u> (2 months)

Technical Demonstration (2 month)

- Install detector/radiation shield to a US reactor.
- Measurement and data analysis.
- Minor improvements on software and algorithm.

<u>Stage 3</u> (12 months)

Measurement at Fukushima Daiichi (3 reactors $\times$ 4 month)

- Setup radiation shields and detector installation.
- Measurement and data analysis.
- Weekly report to TEPCO, Japanese government and DoE.

Planning and equipment acquiring processes can run parallel and, as a result, the GMT is able to be deployed within 3 months after initiating funding, and it would take 1 year to measure Fukushima Daiichi reactor #1-3. If a demonstration at a US reactor site is required, it will delay the start of Fukushima Daiichi measurements by 2 months but would reduce the potential risk of the project to zero.

<u>Planning for Fukushima Daiichi measurement</u> (1 month)

At the very bigining, we will establish the conditions and agreements for collaboration with Japanese government and TEPCO. During the planning stage, five personnel from LANL will make frequent visits to Tokyo and Fukushima; one Japanese-speaking personnel will be stationed in Tokyo to develop a full project plan for actual detector deployment with accurate details regarding cost, scope, and schedule. The engineering concept will be compatible with TEPCO's site clean-up plans. The study will be aided by 3-dimensional visualization computer model of Fukushima Daiichi reactors, already developed by LANL.

The planning will accommodate the possibility of viewing lower regions of the reactor pressure vessel, and it is understood this would imply installing the lower detector below ground level, adjacent to the reactor building. A below-ground detector would facilitate viewing lower regions and also be shielded from site radiation by the surrounding soil. It is estimated approximately two weeks of data collection time would be required to reconstruct an image of the reactor interior, with a spatial resolution of 0.2 m.

Detailed radiation maps of Fukushima Daiichi will be developed, with measurements collected at potential detector installation points, showing levels of γ rays and their energy spectrum. A drift-tube test will be performed at a possible installation point.

Design and manufacture radiation shields (3 months)

One of the engineering challenges in this project is radiation shields that can be installed at Fukushima Daiichi in a short time and has earthquake-resistant support structures that meet Japanese standard. We are considering a plastic cases that can hold water of 1-m thickness. The shield would weight 100 ton when fully loaded with water. The base of the shield will be iron plate of 20-cm thickness. Water will be poured after they are installed to make the installation process easier. The plastic cases is partitioned into three sections (25, 25 and 50 cm) so that an effective thickness of the water shield can be modified. Lesser shield could increase the muon-event rate by 10 % at the cost of increased background events. Location, height, of GMT should be changed without dismantling the shields. The shields will be manufactured in Japan and shipped to the US to be tested at a US reactor site.

We will discuss with some possible construction company in Japan for their design and installation method. The installation procedure and schedule will be supervised by TEPCO.

Manufacturing detector (1 month)

The existing GMT consists of 6-layer drift-tube planes but we plan to upgrade it to 8 layers so that the system is less affected by random coincidences caused by intense γ-ray radiations at the Fukushima Daiichi site. A pair of new GMT consists of 3,456 drift-tube detectors (*fig.7*) with a spatial and angular resolutions of 0.4 mm and 2 mrad (full width at half maximum). We will improve the system reliability to make it almost “maintenance free” so that it can be controlled remotely during the measurement at Fukushima Daiichi. Power supplies for the drift tubes will be upgraded. Cooling for the electronics will be added so that GMT can be operated through out the hot and humid summer of Fukushima.

We have two options to acquire the muon trackers: (1) purchase GMT from Decision Science International Corporation (DSIC), or (2) manufacture them in Japan. We prefer the first option which costs 2 million dollars with a lead time of 3 weeks. DSIC is one of the LANL partners with the MT project. LANL licensed the GMT technology to DSIC, and some of the software were developed at DSIC. We think it is more convenient to manufacture the detector in the US if we plan to work on a demonstration at a US reactor site.

However, the second option would allow convenient local support during the measurement at Fukushima Daiichi. We have not sought this option but KEK and some Japanese companies are renowned in the particle-physics community for manufacturing high-performance detectors. If this option were chosen, LANL could send an engineer and a technician to provide appropriate advices on quality control.

Figure 7: GMT detector used for security interrogation. Photo provided by DSIC.

<u>Specification of GMT</u>

Size & weight:

Drift tube: 5.5 m length (9'), 5.1 cm diameter (2”).
108 tubes/layer, 8 layer/module ($5.5\times5.5\times0.5$ m^3).
2 module/super module.

Operation condition: -10 ~ 40 °C.
<4 mSv/h, <1 mSv/h recommended.

Power consumption:

Data transport: 10GBASE-T to DAQ workstation (~100 m).

<u>DAQ development</u> (3 month)

To handle high event rate caused by the background radiations at Fukushima Daiichi, we will upgrade GMT's electric-circuit boards and their firmwares. In the GMT, analogue signals from drift tubes are digitize by flash ADCs and they are processed with FPGAs before they are sent to a computer. The current system is capable of taking data from each drift tube at the maximum rate of 1 kHz. We will re-design the DAQ system and develop an algorithm that could get rid of γ-ray background up to 4 kHz. The algorithm would be highly parallelized. The upgrade would allow GMT to be operated under radiation environment of 4-mSv/h level. The work will be pursued in collaboration with DSIC's software team.

In the current plan, we will have two workstations: one installed at Fukushima Daiichi, and another for the backup. The initial data processing will be performed at Fukushima Daiichi with the workstation, which discriminates most of the background noises and reduce the data size. Backup computer at KEK will be used to perform the online analysis, and when the workstation at Fukushima Daiichi experiences any trouble, it will be replaced within 24 hours.

A network that connects GMT to a workstation will be upgraded to 10GBASE-T to allow the maximum data transfer rate of 500 MB/s. When drift tubes have average event rate of 4-kHz, the total data rate would be 140 MB/s which exceeds the theoretical limit of 1000BASE-T. We do not plan to use the optical fiber for data transport at Fukushima Daiichi because it is susceptible to radiations.

In the initial analysis, data will be divided into a certain time unit, ~10 ms, so that they can be analyzed in parallel. The workstation is capable of analyzing huge data from GMT using massive cores with a large-shared-memory architecture. The initial data analysis discriminates most of the background by the following two steps, and reduce the data size to less than 1/200:

1. take time coincidence of the events within 1 μs from different drift-tube layers, (~14 MB/s)
2. check the location of the event on the drift-tube-grid to see if the track is valid. (~0.5 MB/s)

Data will be recorded locally, and then transferred to KEK and LANL where they are saved and analyzed.

<u>Software improvement</u> (2 month)

We are planning to further improve our algorithm *e.g.* develop one that combines MT and MR which may help in some cases. An algorithm to combine several measurements with different detector locations (different height), and a 3-dimensional visualization tool will be developed, too.

Most of our software will be improved so that they provide more “user friendly” interface. It is expected that non-LANL personnel may need to operate the system during our measurement at Fukushima Daiichi.

We will rewrite our online-analysis tool, especially, a code that provides initial discrimination of high-rate background. Handling the high event rate caused by the background radiations is a major challenge for the Fukushima Daiichi measurement.

As for the main analysis, we will arrange a powerful computer-cluster at LANL and at Lawrence Berkeley National Laboratory (LBL) so that they could be used almost exclusively for the Fukushima-Daiichi Muon Tomography project. These clusters will analyze tracks and calculate scattering angles of the particles to reconstruct tomographic images of a reactor, and to run simulation for case studies.

<u>Technical demonstration at US reactor</u> (2 months)

As described in the previous section, a mockup demonstration was carried out at LANL. Recently, we were requested by the Japanese government to perform additional technical demonstration using a working reactor in the US. LANL team also proposed the same demonstration so that the risk of Fukushima-Daiichi measurement can be reduced to zero.

In principle, we could use existing GMT which was already made by DSIC since the radiation protection is not needed for the demonstration. However we would like to use a new GMT so that we can practice the installation procedure of a GMT detector, radiation shielding and their mechanical supports to a reactor building. It is anticipated that we could only have a few days to install the setup at Fukushima Daiichi because of the high radiation level of the site. As they say “practice makes perfect”, we will optimize the installation procedure by repeating the process.

Imaging and visualization of the nuclear fuel assembly can be valuable for operating the nuclear-power plant. Though it outsides the scope of the project, we will demonstrate a capability of MT to provide additional peace of mind for daily operation of a reactor.

<u>Detector installation to Fukushima Daiichi</u> (3 days)

At this moment, we do not have a specific procedure and schedule to install GMT at Fukushima Daiichi since supports and advice from TEPCO are crucial. The installation procedure will be discussed with TEPCO in the planning stage.

LANL will send 8 personnel to setup the detector at Fukushima Daiichi. DSIC will send several engineers to assemble the detector before the installation.

<u>Measurement at Fukushima Daiichi</u> (3 reactors × 4 months)

It will require two-weeks of measurement time to see a core image. However, data accumulation of 2~6 months would assess more detailed information of the damage. There are three reactor cores to image, and depending on required needs, additional GMT detectors could be purchased at the cost of \$2.2M/system (includes DAQ and electronics) with a lead time of 3 weeks. This will allow parallel measurements on other cores.

Two LANL personnel will be stationed in Japan during the 1-year measurement to communicate with TEPCO and Japanese government. The LANL team will use KEK as a base to test equipments and to analyze data. There will be frequent video conferences between KEK and LANL to update the latest situation.

DSIC will provide technical consultation whenever needed. We ask TEPCO for the site support at Fukushima Daiichi.

Data analysis (3 reactors × 4 months)

The data measured at Fukushima Daiichi will be sent to KEK and LANL. The combination of Japan and the US based teams allows 24-hour monitoring of GMT. Image reconstruction will be performed using a powerful computer cluster at LANL. Simulation studies to understand the results will be performed at LBL, too.

Images of the first core could be available in one month after starting the measurement. Analyzed images will be sent to TEPCO, Japanese government and DoE on weekly basis. Technical meeting with TEPCO engineers will be held weekly either in Tokyo or at Fukushima Daiichi. Though we do not provide any advices on recovery or decommission planning, we could transfer our images to some reactor experts at LANL and ask them for their opinions, or subcontract reactor specialists in the US, if requested by TEPCO.

LANL-KEK Collaboration

LANL-KEK collaboration was formed in May, 2011, to apply the MT and MR technique to Fukushima Daiichi. We collaborated not only because the two teams are the world's leaders of muon imaging but also because the both methods complement each other to provide valuable input to proceed with recovery and decommission of Fukushima Daiichi. Since we started our collaboration, the two teams have been helping each other and shared essentially all the information on the reactor-imaging techniques, and we will keep our collaboration that way to accomplish our goal.

We believe sharing the information and knowledge is very valuable for the success of this project. The data recorded under the current project will be shared between LANL and KEK teams. There will be no “black box” technology: all the MT software and algorithms developed at LANL will be disclosed to the KEK team at the source-code level. KEK collaborators can modify the codes, develop their own algorithm and publish the results using the data taken under the collaboration.

At the same time, we would like to take this opportunity to form a stronger cooperation between the two leading laboratories of Japan and the US. During the initial stage of the project, LANL will invite some graduate students and postdocs from KEK so that they have opportunities to learn A-to-Z of the MT technology. These students and postdocs are welcomed to join the working-reactor demonstration in the US, and are strongly encouraged to be part of the MT task force during the Fukushima Daiichi measurement. LANL scientists will be pleased to give seminar talks at KEK and at some other institutions during the stay in Japan.

Requested Funding

Because of the nature of the work, it is hard to estimate the cost of the project at this moment. The following tables show rough estimates that covers project planning, purchasing GMT detectors and their shieldings, a demonstration with a working reactor, and measurements of reactor #1-3 at Fukushima Daiichi. Detail cost estimate will be available after planning with TEPCO and a Japanese construction company. Though the project is planned to completes in 18 months, the LANL team would provide technical supports and advice after the project, if official requests were made by KEK and TEPCO.

Japan	(thousand dollars)
GMT detector	2,000
Radiation-shield design	100
Radiation shields	200
Installation to Fukushima Daiichi	500

1-year measurement	800
1-year system maintenance	100
2 postdocs at KEK	150
Travel	50
Total	4,000

US

4 FTE	1,600
Project planning and management	50
DAQ development	500
2 Workstations (installed to Fukushima Daiichi)	50
Software improvement	150
Simulation study	100
US reactor demonstration (KEK team)	350
US reactor demonstration (LANL team)	300
Data analysis on reactor demonstration	100
Data analysis on Fukushima Daiichi	500
Travel and shipping	300
Total	4,000

Team Member

Team members have extensive previous experience of working together and track record of carrying out successful projects.

LANL

K. Borozdin (P-25) was among the initial inventors of MT at LANL, and has been involved in its development ever since, primarily focusing on the modeling and reconstruction algorithms.
S.J. Greene (P-25) is Team Leader of the Threat Reduction Team of the LANL Subatomic Physics Group. Career focuses mainly on medium energy nuclear physics using pions and protons. Has recently led an extensive program investigating active interrogation techniques to detect special nuclear materials. Author/co-author of 67 refereed journal papers.
E.C. Milner (P-25) has specialized in detector development and data acquisition electronics design for experiments probing fundamental properties of muons, kaons, and high energy collisions at LANL, BNL, FNAL, and SSCL. Co-author of over 40 refereed journal papers.
H. Miyadera (AOT-ABS) is specialized in muon physics. Awarded Nishikawa Prize ('05) and Conference Award at International μSR Conference ('02). Developed the world's first large-acceptance muon channel at KEK; lead or participated in muon interrogation experiments.
C. Morris (P-25) developed a variety of radiographic techniques at Los Alamos using neutrons, protons, electrons and muons. Co-author of over 250 refereed journal papers and a Fellow of the American Physical Society and is a Los Alamos National Laboratory Fellow.
J. Perry (ISR-1) is a graduate student from UNM working extensively on data-acquisition system and data analysis. Received LANL Student Award ('11).
D. Seely (LFO-DO) performed research and design for GE Nuclear Steam Supply Systems including research and development on the BWR-6 and Mark-III containments. Has extensive engineering and operating experience at a commercial pressurized water reactor, qualified as a Senior Reactor Operator, and was the plant engineering manager.

LBL

Z. Lukic is expert in astrophysics and high-performance computing. Has performed GEANT 4 simulation for Fukushima Daiichi reactors.

KEK
K. Nagamine is a leader of muon science. Developed pulsed-muon facilities at KEK and RAL. Worked on pioneering work on μSR, muon catalyzed fusion and generation of ultra-slow muon. Developed MR technique for volcano and blast furnace measurements.